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Boundary Shear Stress Across a River Section from in-situ Doppler Profiler Measurements

BOUNDARY SHEAR STRESS ACROSS A RIVER SECTION FROM IN-SITU DOPPLER PROFILER MEASUREMENTS

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ABSTRACT

In this paper, a technique for establishing the boundary shear stress distribution in open channel flows is proposed and used. The boundary shear stress along the wetted perimeter of a large river cross-section was estimated from repeated Doppler profiler (aDcp) campaigns conducted for a range of flow conditions. Experimental vertical velocity profiles were extracted from 18 series of aDcp discharge measurements performed in the Saône river at the Saint-Georges gauging station in Lyon, France. Post-processing methods for aDcp data positioning, averaging and depth-integrating were implemented and applied to each of the 18 aDcp series, in order to establish 23 mean vertical velocity profiles across the 96 m-wide, 10 m-deep cross-section. An average non-dimensional profile was computed from the resulting 414 velocity profiles. It was found that the lowest 70% part of this unit profile can be represented accurately by a log law with a zero-velocity shift (or roughness height) of z_0 = 4-5 mm approximately. This value corresponds to a 50 mm medium grain size for the bed material, which seems consistent with the in-situ observation. Consequently each experimental profile was regressed individually against a log-law, below a maximum relative elevation ζ_c=0.7 only, and assuming the mean value for z_0 (4.6 mm). For each campaign, the mean shear stress and the boundary shear stress distribution along the wetted perimeter were estimated. The mean shear stress was also computed using an energy slope estimate stemming from the Manning-Strickler formula, in which the mean velocity and hydraulic radius were calculated using the aDcp measurements. The resulting mean Manning coefficient was n = 0.026 m$^{-1/3}$.s. The sensitivity of the experimental results to the regression parameters (z_0, ζ_c) was tested and discussed.

Keywords: boundary shear stress, open channel flow, field measurements, acoustic Doppler current profiler (aDcp), Saône river

1. INTRODUCTION

The boundary shear stress distribution is very important in almost all studies of open channel flows, including flow velocity, dispersion, sediment transport and channel migration (Guo and Julien 2001, Paquier and Khodashenas 2002, Atabay and Knight 2007). The boundary shear stress distribution along the wetted perimeter of an open channel is known to be non-uniform and influenced notably by the shape of the channel cross-section (Knight et al., 1994), the longitudinal variation in planform geometry (Pizzuto, 1991), the structure of the secondary flow cells (Nezu and Nakagawa 1993, Knight et al. 2007), and any non-uniformity in the boundary roughness (Knight et al. 1992).

Whereas a number of experimental laboratory studies can be found in the literature

(Lane 1953, Replogle and Chow 1966, Ghosh and Roy 1970, Myers 1978, Knight et al. 1984, Galip et al. 2006), field data for boundary shear stress distributions in rivers are scarce (Kostaschuk et al. 2004, Sime et al. 2007). For laboratory flumes, a range of methods such as log profile, drag, Reynolds and turbulent kinetic energy approaches can be applied for estimating the local boundary shear stress (Biron et al. 2004). For field open channels, the methods based on measured vertical velocity profiles appear as the most convenient. Most commonly, the classical logarithmic law of the wall is assumed to be relevant for a fully turbulent open-channel boundary layer:

$$\frac{u_z}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad (1)$$

with u_z the velocity at elevation z above the bed, κ the von Kármán's constant (= 0.41), u_* the shear velocity, z_0 the roughness height, i.e. the elevation above the bed where the velocity is zero. The shear stress writes:

$$\tau = \rho\, u_*^2 \qquad (2)$$

Regressing u_z against ln(z) directly provides estimates of u_* and z_0. Due to the imperfect knowledge of the near-bed velocity profile, this technique usually yields u_* estimates with poor repeatability (Wilcock 1996). Given a z_0 estimated value, computational methods from a single measured velocity or from the depth-averaged velocity are more repeatable. The roughness height z_0 may be estimated from a modified Nikuradse formula:

$$z_0 = aD_x/30 \qquad (3)$$

with a a constant (typically 2-4 in field conditions), D_x a representative grain-size for which x% are finer, typically ranging between 65% and 90% (Whiting and Dietrich 1990). The formula has to be modified from the original Nikuradse expression (i.e. a=1, $D_x = D_{50}$) derived for homogeneous substrates without bedforms and sediment transport.

This paper reports the mean shear stress values and the boundary shear stress distributions along the wetted perimeter estimated from repeated aDcp campaigns in a large river section for a range of flow conditions. First, the protocols for field data acquisition and post-processing are presented. Then, the mean roughness height z_0 and the maximum relative elevation ζ_c below which the profiles follow the log law are derived, and the sensitivity of the experimental results to the regression parameters (z_0, ζ_c) is evaluated and discussed. Finally, conclusions about the suitable procedure for estimating field boundary shear stress are summarized.

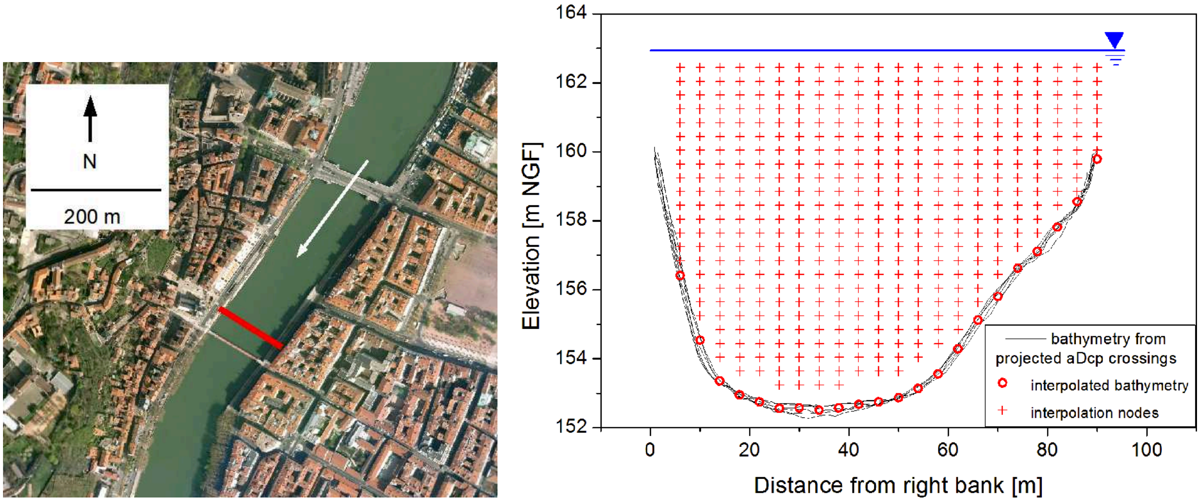
2. ADCP FIELD MEASUREMENTS

2.1 Experimental sites, methods and flow conditions

Field measurements were carried out by the Cemagref and the Compagnie Nationale du Rhône (CNR) in the Saône river in Lyon, France (Fig. 1-a). The site corresponds to the CNR Saint-Georges (referred to as SG hereafter) gauging station located in a straight reach of the river 4 km upstream the confluence with the Rhône river. This river reach is hydraulically influenced by the dams of the CNR Pierre-Bénite hydropower plant situated 4 km downstream the confluence. The cross-section shows an asymmetrical trapezoidal shape.

High spatial resolution bathymetry and 3D velocity field measurements were acquired with vessel-mounted 4-beam acoustic Doppler current profilers (aDcp) manufactured by Teledyne RDI: ADCP® WorkHorse RioGrande operating at 600 or 1200 kHz were used. Standard configuration and deployment procedures for river discharge measurement were followed. Each aDcp series corresponds to 6 (exceptionally 5 or 7) successive aDcp crossings.

Flow velocities were acquired through the default Teledyne RDI broadband mode 1 (WM1). The velocity bin size (WS) was set to 0.30-0.40 m and measured velocities were 5-ping-averaged (WP5). All data were referenced to the aDcp bottom-tracking (mobile-bed tests indicated no significant positioning bias even for the highest discharge values).



a) b)

Figure 1 experimental site (Saint-Georges gauging station, Saône river in Lyon, France)
a) Aerial view and aDcp transect (red line); b) averaging grid for a given aDcp campaign (6 replicate aDcp crossings, campaign n°2)

Table 1 Summary of hydraulic conditions for the 18 aDcp campaigns.

Campaign number	Hydraulic radius R_h (m)	Width-depth ratio	Energy slope J ($\times10^{-5}$)	Discharge Q (m^3/s)	Flow velocity U (m/s)	Froude number F	Reynolds number R ($\times10^6$)
1	7.52	9.7	16.5	1352	1.91	0.22	14
2	7.56	9.3	20.9	1580	2.20	0.26	17
3	6.96	9.0	0.2	115	0.17	0.02	1.2
4	7.80	9.0	24.0	1768	2.29	0.26	18
5	7.06	8.6	0.7	246	0.36	0.04	2.5
6	7.04	8.6	1.1	317	0.46	0.05	3.3
7	6.88	9.8	3.3	512	0.79	0.10	5.4
8	7.88	9.4	22.4	1787	2.29	0.26	18
9	7.06	9.9	8.9	902	1.37	0.17	9.6
10	7.14	9.6	12.6	1068	1.53	0.18	11
11	7.83	9.4	13.4	1242	1.62	0.18	13
12	7.87	9.3	13.1	1347	1.75	0.20	14
13	7.55	8.8	16.8	1335	1.86	0.22	14
14	7.07	9.3	5.6	692	1.04	0.12	74
15	7.02	9.6	3.0	510	0.78	0.09	5.5
16	7.28	9.0	11.0	1035	1.45	0.17	11
17	7.93	9.5	19.9	1552	2.05	0.23	16
18	7.07	9.1	0.8	262	0.38	0.04	2.7

Eighteen aDcp campaigns were conducted at Saint-Georges during a series of flood events in February-April, 2006. For each campaign timespan, stationary conditions were checked from staff gauge readings, pressure gauge recordings and velocity monitoring from a fixed side-looking Doppler profiler (H-aDcp) installed in the river bank. Flow rates ranged between 100 and 1800 m^3/s. A summary of the most important hydraulic parameters during the 18 aDcp campaigns is given in Table 1. Note that the energy slope is computed from the measured average shear stress (see section 3.2).

2.2 **Post-processing of aDcp data**

Post-processing methods used here for positioning and averaging aDcp data from several replicate crossings are reported in details in Le Coz et al. 2007.

The bottom tracking data were used to derive the aDcp East/North position relatively to the beginning point of each transect. No moving bed effects were detected and the bottom-track was unbiased. The data were referenced horizontally and vertically from shore distance measurements, and water level and transducer depth measurements respectively.

For each series, the 3D velocity and 4-beam-averaged bathymetry data were normally projected onto a vertical averaging grid with transverse and vertical space steps 4m and 0.4m respectively (Fig. 1-b). Inverse Distance Weighted (IDW) average of all neighbouring data within 2m was computed for bathymetry and velocity measurements.

For each vertical profile, the depth-integrated velocity U was computed using the Teledyne RDI integration procedure (WinRiver User's Guide 2003) with constant extrapolation in the top unmeasured layer and one-sixth power law in the near-bed unmeasured layer. For each campaign the discharge was also computed following the WinRiver computation procedure. The comparison of the resulting discharges with the average discharges obtained with the WinRiver software from the replicate aDcp crossings led to relative deviations typically lower than 1% and no significant bias over the 18 gauging series (-0.3%).

Typical instrumental statistical errors mentioned by the manufacturer for bathymetry (around 0.1m) and velocity (a few cm/s) measurements are quite acceptable in comparison with usual currentmeters performance. Such statistical errors can be reduced by averaging pings as well as by averaging replicate aDcp crossings. Averaging post-processing procedures like those performed for this study usefully reduce velocity data dispersion due to turbulence-induced time-fluctuations and to the Doppler technology noise. Sime *et al.* (2007) and Szupiany *et al.* (2007) recognized that averaging aDcp crossings significantly improves the repeatability of shear stress estimates. As the water depth scales with 10 m approximately, uncertainty associated with the bed level estimate should have a limited impact on shear stress estimates.

3 COMPUTATION OF THE BOUNDARY SHEAR STRESS

3.1 **Determination of the cut-level (ζ_c) for the log law of the wall**

The relevance of applying the log law of the wall to velocity vertical profiles over the whole flow depth h or partially can be checked experimentally. The elevation $\zeta_c = z/h$ above the bed up to which the regression is computed must be chosen carefully (Biron *et al.* 1998). From flume experiments on uniform smooth flows, Cardoso *et al.* (1989) observed that the law of the wall describes accurately the flow in the inner region ($z/h < 0.2$) of the boundary layer and also in the outer region, at least for $0.2 < z/h < 0.7$, where the wake appears to be weak. This observation is also consistent with in-situ data from rough turbulent flows that may even follow a logarithmic profile over the whole flow depth (Smart 1999).

Through mathematical error analysis, Yu and Tan (2006) pointed out that regression methods with a priori fixed roughness height should be applied to the highest velocity data (still in the log layer), in order to reduce the uncertainty associated with the shear velocity estimates. Indeed the near-bed velocity profile is very sensitive to the bed level and roughness height estimates. In the case of aDcp measurements, the quality of near-bed velocity data is affected by side-lobe interference, beam separation and parasite echoes from solid surfaces. For a beam separation angle of 20°, velocity data are compromised by side-lobe interference for $z/h < 0.06$ approximately.

The maximum elevation above which the vertical velocity profile deviated from the logarithmic law was defined experimentally from the average non-dimensional vertical profile derived from the 18 gauging campaigns at SG site (414 experimental profiles across the section). The average and standard deviation of u_z/U were computed in 0.04-high vertical bins. The standard deviation increased near the bed and the free-surface but remained lower than 0.08 all over the flow depth and lower than 0.05 for $0.25 < z/h < 0.90$. Fig. 2 shows that the average profile reasonably followed the log law up to $\zeta_c = 0.7$, which corresponds to the core of the outer region defined by Cardoso *et al.* (1989).

According to the considerations mentioned above, all vertical velocity profiles measured at SG site were systematically truncated to $0 < z/h < 0.7$ before linear regressing.

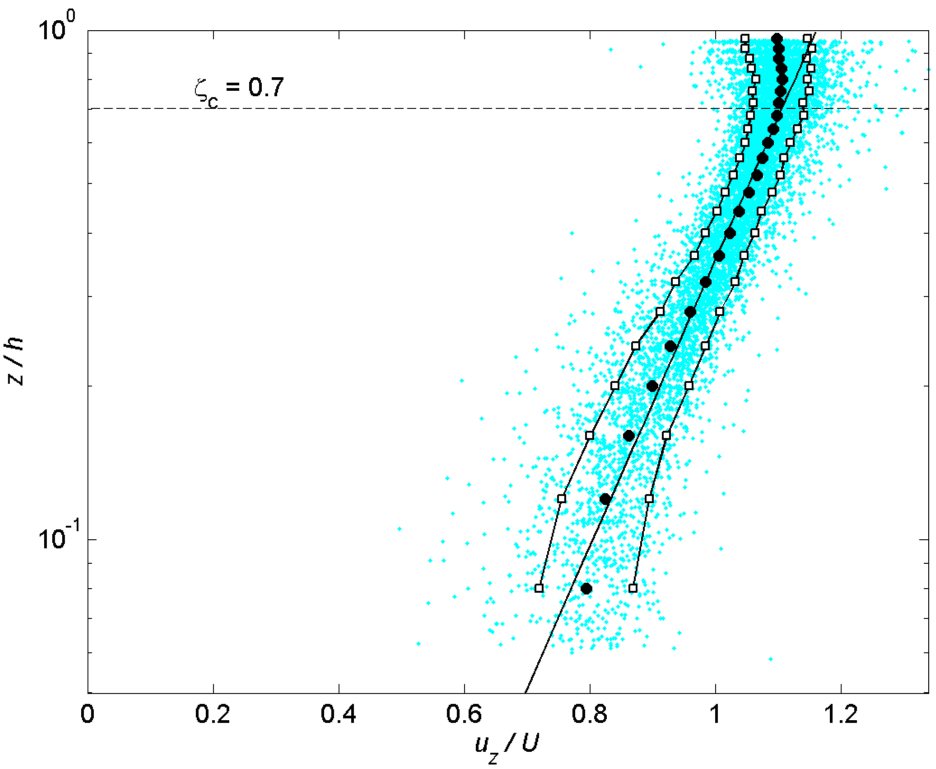


Figure 2 Non-dimensional vertical velocity profiles (dots) at SG site computed from all 414 velocity profiles (all aDcp campaigns, all positions throughout the cross-section): non-dimensional elevation z/h vs. average velocity u_z/U (circles) with logarithmic law fit (bold line) up to $z/h = 0.7$ (dashed line). Experimental standard deviations are indicated by squares.

3.2 Estimation of a fixed roughness height z_0

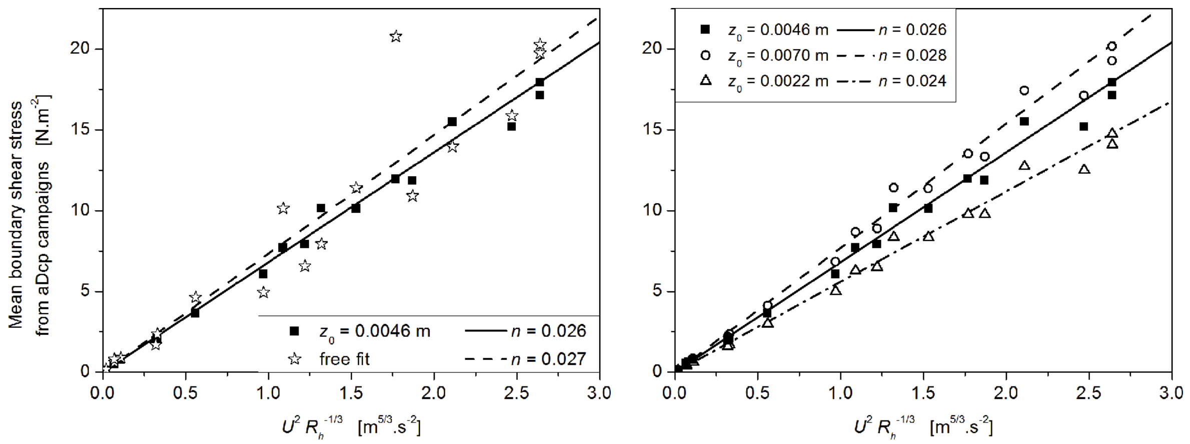
As expected, u_* and z_0 derived from unconstrained linear regression appeared to be quite dispersed and resulting linear correlation coefficients are frequently poor ($R^2 < 0.80$). To tackle this shortcoming, the linear regression was constrained by adding to each profile the pair (u_0=0, z_0). This method can be seen as a hybrid technique between unconstrained regression and fixed z_0 techniques (single velocity, depth-averaged velocity). The aim is to exploit the whole information contained in the aDcp-measured velocity profile, while constraining the fitted profile to a realistic shape in the vicinity of the bed. This technique is very close to the "global method" proposed and used by Cheng et al. (1999).

To estimate a unique z_0 value for all profiles at SG site, the mean z_0 was computed as the average of the $\ln(z_0)$ derived from the unconstrained regression of all 414 profiles. Cheng et al. (1999) recognized that this "log-averaged method" is more accurate than the arithmetic average of the z_0 obtained by the conventional method. Discarding irrelevant log fits with $R^2 < 0.80$ and $u_* < 0$, the mean z_0 is equal to 0.0046 m with experimental standard deviation 0.0012 m. This value is coherent with the log profile regressed on the average non-dimensional profile: the fitted z_0/h is 5.5×10^{-4}, i.e. $z_0 = 0.0044$ m with an average $h = 8.02$ m. Following Eq. 3, this z_0 value would correspond to a representative grain-size D_x of 0.05 m. No quantitative grain-size data are available, but this order of magnitude is consistent with the expected size of the bed material.

The constant value retained for z_0 is likely to constitute the main source of uncertainty associated with the derivation of u_* following the hybrid regressing technique used here. To assess this uncertainty, the sensitivity of the cross-section-averaged aDcp boundary shear stress $\tau_{0,a}$ to z_0 was tested. The mean shear stress $\tau_{0,a}$ was computed as the integration of the local boundary shear stress values along the wetted perimeter and compared with the mean shear stress $\tau_{0,n}$ computed using the energy slope given by the Manning-Strickler formula:

$$\tau_{0,n} = n^2 \rho g\, U^2 R_h^{-1/3} \qquad (4)$$

with n the Manning coefficient, ρ the water density, g the gravity acceleration, U and R_h respectively the mean velocity and the hydraulic radius computed from the aDcp measurements.



a) b)

Figure 3 Mean boundary shear stress measured at SG site vs. $U^2 R_h^{-1/3}$
a) for $z_0 = 0.0046$ m (N=18; R^2= 0.99) and unconstrained fit (free z_0, N=18; R^2=0.89);
b) for $z_0 = 0.0046$ m $\pm$ 2 $\times$ 0.0012 m (N=18; R^2=0.99).

Fixing the z_0 value before regression is equivalent to fixing the roughness coefficient. If the mean z_0 value (0.0046 m) is imposed, linear regression against $U^2 R_h^{-1/3}$ yields a Manning coefficient $n = 0.026$ (Fig. 3-a). If z_0 is kept free (unconstrained log fits), $\tau_{0,a}$ data appear much more scattered than if z_0 is fixed. Still, $\tau_{0,a}$ may be modelled by the Manning-Strickler formula reasonably well. The resulting Manning coefficient $n = 0.027$ is very close to the one corresponding to the fixed mean z_0. This test shows that selecting the mean z_0 as the fixed z_0 value does not bias the mean boundary shear stress. Therefore regressing velocity profiles with added point ($u(z_0) = 0, z_0$) is an advantageous method for estimating local boundary shear stress, as it takes into account the whole profile information (like the usual regressing method), reduces the scatter of estimates (like the usual z_0 fixed methods), and does not bias the mean shear stress value.

Fig. 3-b shows that for z_0 = 0.0046 m, 0.0070 m, 0.0022 m (i.e. mean value ± 2 × experimental standard deviation) respectively, $\tau_{0,a}$ varies linearly with $U^2R_h^{-1/3}$, with correlation coefficients close to R^2=0.99. The average deviations to the linear regression are -2.5%; -4.2%; -2.3%, respectively (the negative bias is mainly due to a large negative deviation for campaign 3). The corresponding Manning estimates from the regressed slope are close to each other (n = 0.026, 0.028, and 0.024, respectively).

3.3 Non-dimensional boundary shear stress distribution

Tests were also conducted to assess the sensitivity of the shear stress distribution across the section on the regression parameters (z_0, ζ_c). As a typical example, Fig. 4 and Fig. 5 show the shear stress distributions computed from the aDcp campaign n°8. Results were considered whatever the quality of the linear regression, i.e. no condition on R^2 was used.

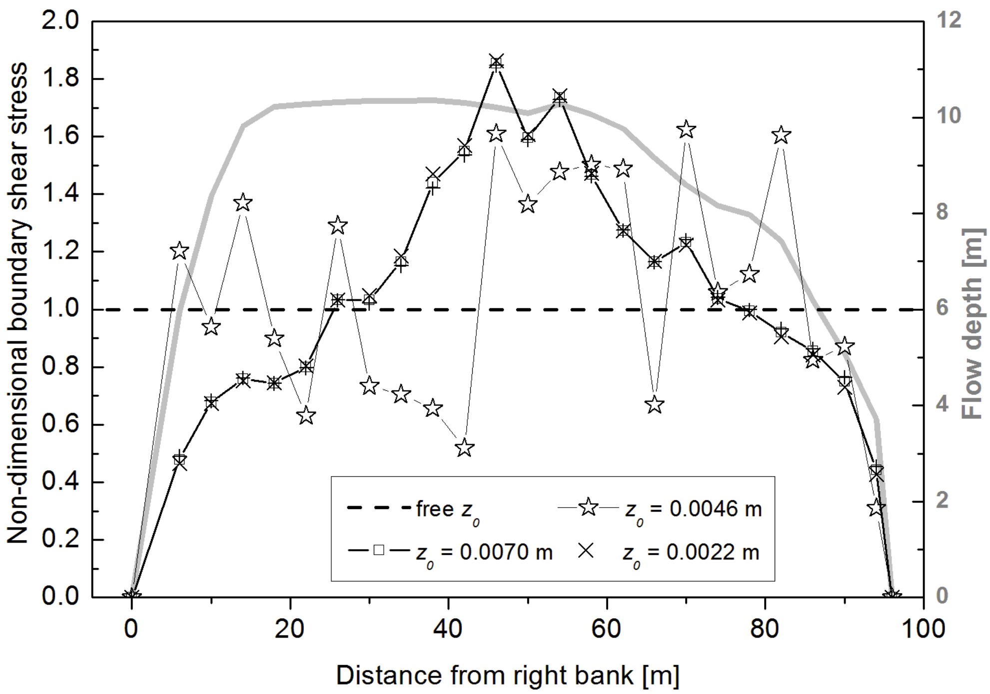


Figure 4 Non-dimensional boundary shear stress distribution (campaign n°8); sensitivity test for z_0 = 0.0046 m; 0.0070 m; 0.0022 m (ζ_c = 0.7).

Almost no change in the non-dimensional shear stress distribution was found for constrained regressions with z_0 = 0.0046 m, 0.0070 m; 0.0022 m and ζ_c = 0.7 (Fig. 4). However, the distribution obtained from unconstrained fits (free z_0) appeared much more scattered with almost no clear pattern along the wetted perimeter. This confirms the efficiency of fixing the site-specific mean z_0 value derived from all log fits, thus providing smooth boundary shear stress estimates.

For the same aDcp campaign, z_0 was fixed to 0.0046 m and ζ_c was given 3 different values (Fig. 5). The value ζ_c = 0.7 was derived from the observed mean velocity profile; ζ_c =

0.2 corresponds to the usually recognized log-layer; ζ_c = 1 corresponds to log fits over the whole depth. The overall shear stress distributions were found to be very similar whatever the value assigned to ζ_c. However, some discrepancies appeared locally (especially the position of the maximum shear stress) between ζ_c = 0.2 and the two other configurations. As discussed above, performing the regression for the 20% lowest part of aDcp velocity profiles might be questionable as the quality of measurements is poorest in the vicinity of the bed.

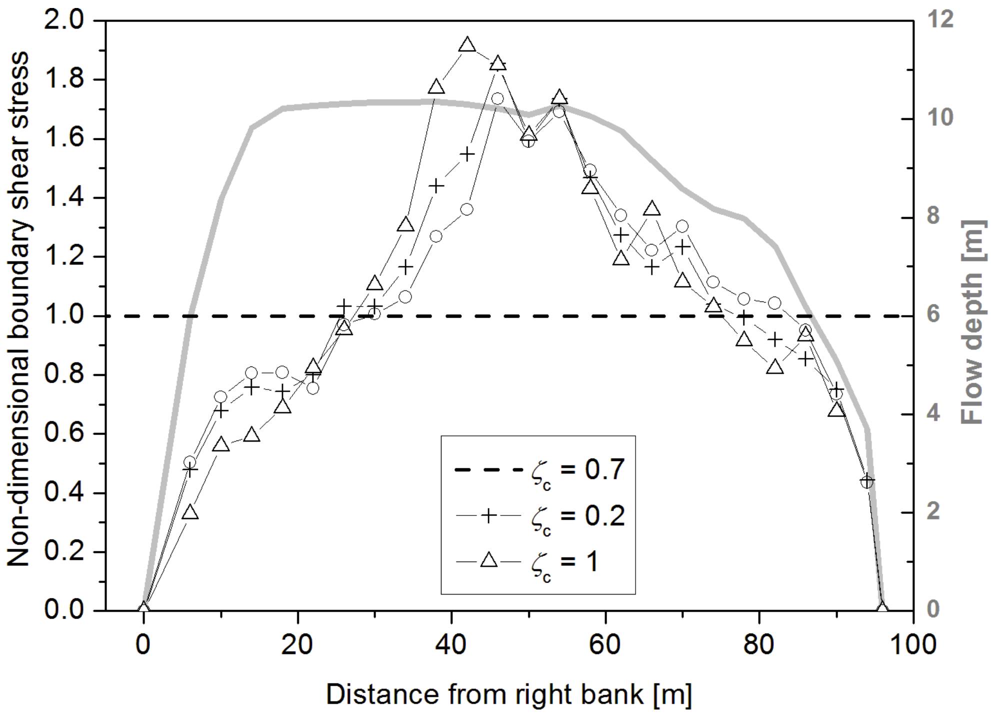


Figure 5 Non-dimensional boundary shear stress distribution (campaign n°8); sensitivity test for ζ_c = 0.7; 0.2; 1 (z_0 = 0.0046 m).

CONCLUSIONS AND PERSPECTIVES

The boundary shear stress along the wetted perimeter of a large river section was estimated from repeated Doppler profiler (aDcp) campaigns for a range of hydraulic conditions. Post-processing methods for aDcp data positioning, averaging and depth-integrating were implemented and applied to each of the 18 aDcp series. An average non-dimensional profile was computed from the resulting 414 profiles. The lowest 70% part (cut-level ζ_c=0.7) of this unit profile can be represented accurately by a log law with a zero-velocity shift (or roughness height) of z_0 = 4-5 mm approximately.

Consequently the lowest 70% parts of each experimental profile were regressed individually against a log-law, assuming a constant value for z_0. For each flow discharge value, the mean shear stress value and the boundary shear stress distribution across the wetted perimeter were estimated. The mean shear stress values were also computed with an energy slope estimate stemming from the Manning-Strickler formula, in which the mean velocity and the hydraulic radius were calculated using the aDcp measurements. The resulting mean Manning coefficient was n = 0.026 $m^{-1/3}$.s.

The sensitivity of the experimental results on the regression parameters (z_0, ζ_c) was tested and discussed. Regressing velocity profiles with added point ($u(z_0)$ = 0, z_0) is an advantageous method for estimating local boundary shear stress, as it takes into account the whole profile information (like the usual regressing method), reduces the scatter of estimates (like the usual z_0 fixed methods), and does not bias the mean shear stress value.

Quantifying the uncertainty associated with boundary shear stress derived from local aDcp velocity profiles is beyond the scope of this paper. In particular, one must recall that possible biases are difficult to assess in the absence of concurrent measurements, such as drag, Reynolds and turbulent kinetic energy approaches applied to flume cases (Biron et al. 2004). Potential sources of uncertainty need to be investigated. Three main sources of uncertainty can be distinguished (Bauer *et al.* 1992): i) instrumental and deployment uncertainty associated with velocity and position measurements; ii) deviation of the real flow from the log law; iii) statistical errors associated with the derivation of u_* and z_0 (Wilkinson 1984). The proposed methodology for establishing the boundary shear stress from aDcp measurements intends to address these 3 points, by i) averaging field data with proper post-processing steps; ii) determining the highest level ζ_c for log fits from the shape of experimental velocity profiles; iii) constraining the roughness height with the mean z_0 value over all profiles.

New technologies such as Doppler profiling, associated with proper data analysis, offer new perspectives for providing hydraulicians with boundary shear stress measurements from real river cases. Such field datasets will be valuable for evaluating the effectiveness of various existing numerical models and geometrical methods at predicting the boundary shear stress distribution in river cross-sections.

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